CHAPTER 4
ICE FORECASTING

4-1. General. Forecasting of ice conditions on inland waterways is based on the premise that, given forecasts of future meteorological conditions and forecasts of future hydraulic conditions, it is possible, through knowledge of thermodynamics, open channel hydraulics, ice physics, and an understanding of the behavior of the various forms of river ice, to develop forecasts of the future ice conditions. The methodology described in this chapter produces ice forecasts that are unique to a specific river or basin for which an Ice Forecasting System is developed.

a. The first goal of an Ice Forecasting System is to anticipate the period when ice formation is possible and, if possible, assign probabilities to the likelihood of formation. This type of forecast is known as a Long-Term Water Temperature Forecast. Such forecasts are made by a computer model of the overall heat balance of the river watershed, which indicates the long-term water temperature response to changes in air temperature.

b. A second type of forecast is much more detailed in its results. The goals of this type of forecast are to predict the reaches of a river where ice will form, when that ice will form, the area1 extent of stationary ice, the ice thickness, the time of breakup, and ice jams and other extreme ice conditions. This Mid-Winter Ice Forecast is very sensitive to day-to-day changes in meteorological conditions and flow conditions, making it apply to a much shorter time, generally five to seven days. This short-term forecast requires the development of three closely interrelated models: first, a dynamic flow model to simulate the channel hydraulics, including the influence of ice; second, a thermodynamic model to simulate the heat transfer between the waterway and the atmosphere; and third, an ice formation model to distribute the ice along the waterway and to calculate the ice thickness.

c. In this chapter, general overviews of the Ice Forecasting System, including the Long-Term Water Temperature Forecasts and the Mid-Winter Ice Forecasts, are presented. For each type of forecast, its objective, the basic theory, the model operation, the data required for model calibration, the data required for model operation, and the results are discussed.

Section I. Long-Term Water Temperature Forecasts

4-2. Objective. Predictions of water temperature are made primarily to estimate when the water temperature will be at or near the freezing temperature, 32°F. It is at this time that ice can be expected to form. Advance knowledge of the date that freezing temperatures will be reached allows efficient management of resources necessary to deal with the problems that can be caused by ice at locks and dams and other Corps facilities, and may assist operational planning for other navigation interests.

4-3. Model Description. River water temperatures reflect the balance of heat flow into and out of the volume of water that makes up the river discharge. This principle forms the basis of river water temperature forecasting. At any point along a river, the water temperature at that point reflects the heat balance upstream of that point. Mathematically, this temperature can be represented by a convectiondiffusion equation. However, this equation can require a great deal of information to solve, and much of the information may not be known for future times. An efficient alternative is a total watershed approach. This approach assumes the following:

— The temperature of the river is well-mixed vertically, that is, the temperature of the river is uniform from the surface to the bottom. (This will be true of almost all rivers with any velocity. This may not be true of reservoirs, lakes, or other large bodies of water without appreciable flow velocity.)

— The heat flow into and out of the river water is dominated by exchanges with the atmosphere. (This allows the prediction of the river water temperatures to be based on forecasts of future meteorological conditions. Other heat sources, such as industrial or municipal effluents, can be factored into the forecast by studying past response of the river water temperature. However, if the water temperature of the river upstream of the point for which the forecast is to be made is dominated by such sources, this approach may lead to large inaccuracies.)

— The river is essentially free-flowing, having only a relatively small portion of its drainage area covered by reservoirs or lakes, the temperatures of which are not dominated by artificial heat sources.

a. Heat Transfer Components. There are many components of the heat balance that affect and determine the actual resulting river water temperature. These include heat transfer to the atmosphere, heat transfer to the ground, the influx of groundwater, and artificial heat sources. As stated previously, the heat transfer is dominated by the exchange with the atmosphere. This exchange has many modes, including long-wave radiation, short-wave radiation, evaporation, condensation, and precipitation. However, many of these modes are difficult to forecast, and forecasts of them are not generally made. Therefore, a simple but generally accurate means of approximating the heat transfer rate f is made based on the formula

$$\phi = h_{wa}(T_w - T_a) + q \tag{4-1}$$

where

T_a = temperature of the air
T_w = temperature of the water
h_{wa} = effective heat transfer coefficient from the water to air
q = heat inflow that is independent of the air temperature, such as solar radiation.

b. Convection-Diffusion Equation. In this watershed approach, the one-dimensional convection-diffusion equation can be simplified to the form

$$\frac{DT_w}{Dt} = -\frac{\phi}{\rho C_p D} \tag{4-2}$$

where

D/Dt = total derivative
ρ = density of water
C_p = specific heat of water
D = mean channel depth.

c. Air Temperature Representation. In principle, the average daily air temperature over the entire period of a year can be represented by a Fourier series. However, in practice, it is efficient to represent the actual mean air temperature on any day by

$$T_a = \overline{T} + a \sin\left(\frac{2\pi t}{T} + \theta\right) + T_{\delta_j} \tag{4-3}$$

where

t = Julian date
T = number of days in year (365 or 366)
θ = phase angle
$\overline{T}$ = mean annual air temperature
a = amplitude
T_{δ_j} = deviation in air temperature.

The deviation in air temperature represents the difference between the actual daily average air temperature and the sum of the yearly mean temperature and the first harmonic representation of the daily average air temperature. The values of $\overline{T}$, a, and θ can be found by analyzing air temperature records from previous years that have been collected in the region where the water temperature forecasts are to be made. Examples are shown in Table 4-1. The deviations of daily average temperature from the first harmonic representation for all past data can be calculated. The deviations for future times are, of course, unknown.

Table 4-1. Mean annual air temperatures and first harmonic coefficients determined for selected first-order National Weather Service stations, for application to the air temperature representation in the Long-Term Water Temperature Forecast model.

Station	*Mean annual air temperature* $\overline{T}$ *(°C)*	*Amplitude* a	*Phase angle* θ	*Period of record*
Pittsburgh,Pennsylvania	10.16	12.64	-1.9085	1965-1982
Huntington, West Virginia	12.63	11.66	-1.8734	1965-1982
Covington, Kentucky	11.80	12.84	-1.8866	1965-1982
Louisville, Kentucky	13.39	12.43	-1.8769	1965-1982

d. Model Parameters. By substituting Equations 4-l and 4-3 into Equation 4-2 and integrating to solve for T_w, an equation describing water temperature is derived.* This equation is the basis of the water temperature forecast model. There are two coefficients in this equation, the response coefficient K_r, and the equivalent temperature T_q. The forecast of the water temperature on day $j (T_{w\,j})$ is based on information known from the previous day, j -1. The forecast is made in one-day increments, starting from the date of the forecast. In principle, the forecast can extend indefinitely into the future. However, in practice, the forecasts are limited by the lack of knowledge of future air temperature deviations.

e. Data Required for Model Calibration. The unknown coefficients in the model equation, K_r and T_q, must be determined by analyzing past air temperature records and water temperature records. This suggests the importance of complete and accurate temperature records for forecasting. Generally, the water temperature records are the most difficult to obtain. The unknown coefficients are estimated by a least-squares approach. † The results of calculating the response coefficient and equivalent temperature for six stations on the Ohio River are shown in Table 4-2. In this case separate coefficients have been calculated for two three-month periods: October through December, and January through March. These two periods cover the entire winter season.

4-4. Model Operation. From the analysis of previous data, the following information is known-air temperature characteristics (mean annual air temperature, first harmonic amplitude, and phase angle), and the water temperature response coefficient and equivalent temperature. From real-time water temperature measurement stations at each location where forecasts are to be made, the actual river water temperatures at the time of the forecast are obtained. The forecasts of air temperature are obtained from the National Weather Service (NWS). Generally, these are represented as

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*The general equation for T_w, for a specific day j, is given by:

$$\begin{aligned} T_{w_j} &= \bar{T} + a\cos\alpha\sin\left(\frac{2\pi t}{T} + \theta - \alpha\right) \\ &+ \left[T_{w_{j-1}} - \bar{T} - a\cos\alpha\sin\left(\frac{2\pi(t-1)}{T} + \theta - \alpha\right)\right] e^{-K_r} \\ &+ T_{\delta_j}(1 - e^{-K_r}) + T_q(1 - e^{-K_r}) \end{aligned}$$

where $\alpha = \tan^{-1}(2\pi/K_r T)$.

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† The coefficients are estimated by minimizing a function Φ:

$$\Phi = \sum_{j=1}^{n} \left(T_{w_a} - T_{w_j}\right)^2$$

where T_{w_a} is the actual water temperature on day j, and T_{w_j} is the water temperature forecast for that day using known values of a, θ, T_{δ_j}, and $\bar{T}$.

Table 4-2. Sample model coefficients for six stations on the upper Ohio River, for application to Long-Term Water Temperature Forecasts.

	Response coefficient K_r		*Equivalent temperature* T_a	
Location	*Oct-Dec*	*Jan-Mar*	*Oct-Dec*	*Jan-Mar*
Emsworth L&D*	0.1737	0.0725	1.35	3.45
South Heights, Pennsylvania (ORSANCO)	0.0637	0.0697	1.35	3.45
Montgomery L&D	0.1087	0.0706	1.27	3.52
Hannibal L&D	0.0998	0.0700	0.20	2.95
Racine L&D	0.1000	0.0633	0.20	1.80
Meldahl L&D	0.0596	0.0594	0.20	1.79

*Lock and Dam.

deviations from the normal air temperature as described by Equation 4-3. A diagram of the model is shown in Figure 4-l. Generally, the model is run to estimate the period when ice formation is possible, that is, when the water temperature is 32°F. However, this would not be a conservative estimate because unforecasted deviations in air temperature may cause the water to reach 32°F

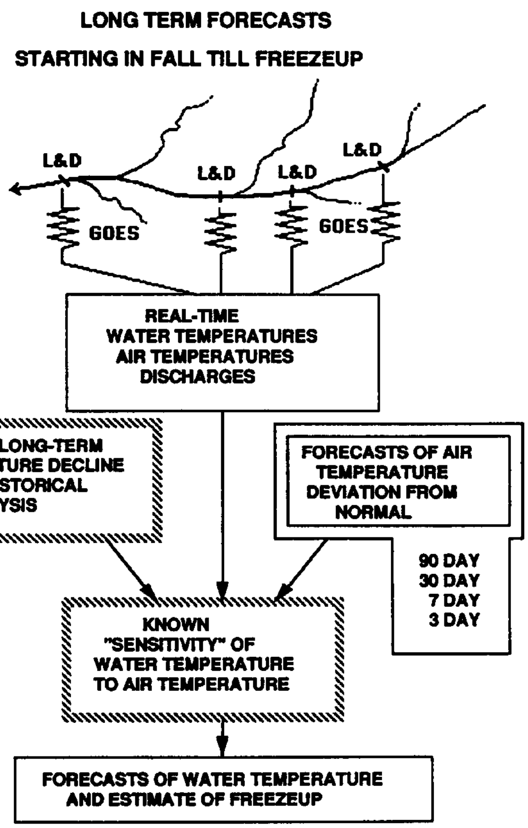

Figure 4-1. Flowchart of Long-Term Water Temperature Forecast model.

sometime before the actual forecasted date, and often, for a given winter season, 32°F may never be reached. Therefore, the following nomenclature has been developed. The term *most-likely ice period* is used to describe the time when the water temperature is forecasted to be 34.7°F (1.5°C) or less. The term *ice watch* is used to describe the time when the water temperature is forecasted to be 32.9°F (0.5°C) or less.

4-5. Model Results. An example of a sample water temperature forecast is shown in Figure 4-2. This example indicates the location of the forecast, the date of the forecast, the water temperature on the date of the forecast, and the air temperature forecasts provided by the NWS. In this case the NWS forecasts are for normal temperature, that is, the temperature deviations from the temperatures described by Equation 4-3 have been set to zero. Then the example provides the actual forecasted water temperature and a description of the *most-likely ice period* and the *ice watch* period.

RIM WATER TEMPERATURE FORECAST

SITE: Emsworth Locks and Dam
Ohio River Mile: 6.2

Date of Forecast: 4 October 1987

Water Temperature: 59.0°F (15.0°C)

Air Temperature Forecasts: 3 Day: NORMAL
7 Day: NORMAL
30 Day: NORMAL

	FORECASTED WATER TEMPERATURE	
DATE	°F	“C
01 Nov 87	50.4	10.2
01 Dec 87	39.6	4.2
15 Dec 87	35.4	1.9
01 Jan 88	32.4	0.2
15 Jan 88	33.4	0.8
01 Feb 88	33.8	1.0
15 Feb 88	34.7	1.5

MOST LIKELY ICE PERIOD: 19 Dec 87 - 15 Feb 87

ICE WATCH: 27 Dec 87 - 5 Jan 88

Figure 4-2.Typical output information of the Long-Term Water Temperature Forecast model. Successive model runs (updates) would yield more precise estimates of the most-likely ice *period and the* ice watch *period.*

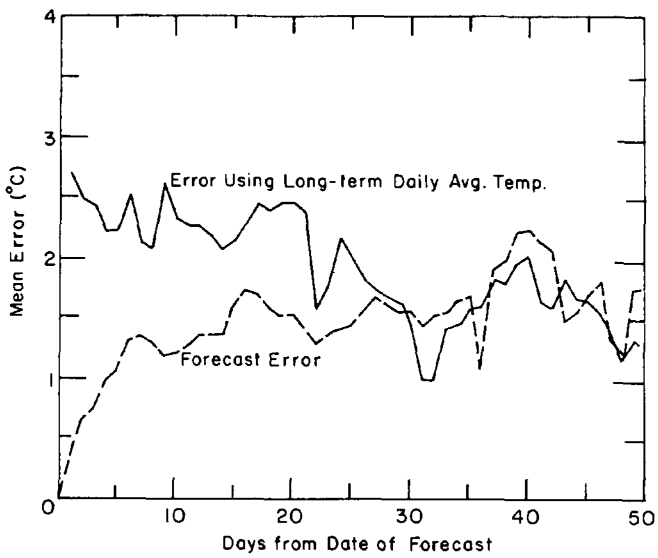

Figure 4-3. Forecast-model accuracy illustrated by plot of error as a function of days since forecast was made. Forecast naturally has its greatest accuracy immediately following the date of forecast, after which error generally increases with time. For comparison, error resulting from simple long-term daily average water temperatures is also shown, and seen to decrease slightly with time. For the period up to about 25 days after a forecast is made, the error in forecasted water temperatures is more acceptable than that associated with reliance on long - term averages.

4-6. Model Accuracy. To assess the accuracy of the Long-Term Water Temperature Forecast model, the Ohio River Valley Sanitation Commission (ORSANCO) station at South Heights, Pennsylvania, has been used because of its long period of record. There are several ways of assessing the accuracy of the forecast. The first is to determine the mean error of the forecast, that is, the average absolute value of the difference between the forecasted water temperature and the actual. Results of forecasts done on 14 years of records are shown in Figure 4-3. The error is calculated based on the forecast that could be made by assuming that a perfect air temperature forecast is available, that is, by using the actual recorded daily average air temperature. It can be seen that, for the 25 day period following the date of the forecast, the forecasted water temperatures are more accurate than those determined by simply using the long-term mean water temperature as an estimate.

Section II. Mid-Winter Ice Forecasts

4-7. Objectives. The objectives of the Mid-Winter Ice Forecasts are to provide accurate predictions of the reaches of a river system where ice will be formed, the reaches of a river system where there will be stationary ice cover, the thickness of the stationary ice cover, the thickness of frazil ice deposited under the ice cover, the water temperature in every reach, and the breakup date of the stationary ice cover. These predictions are to be made as far into the future as possible. However, owing to limitations of weather forecasts, the ice forecasts have a realistic limitation of 5 to 7 days.

4-8. Forecast Model Description. The Mid-Winter Ice Forecast model is composed of three submodels and several supporting models. The Mid-Winter Ice Forecast model also has several items that must be specified; these are known as System Parameters. The three submodels are the Hydraulic Model, the Thermal Model, and the Ice Model. Each of these submodels is based on physical principles that will be discussed below. Moreover, each of these submodels has several items that must be entered as input; these are the Physical Parameters and the Initial Conditions. The Initial Conditions define the river system at the time the forecast is made. Each submodel must also be supplied with parameters known as Boundary Conditions; these are not determined by the ice forecast model, but rather are independently forecasted parameters (such as air temperature and tributary discharge) that drive the ice forecast model. The ice forecast model uses the Boundary Conditions to predict new values of the parameters supplied as Initial Conditions at each time step. These new values are the output of the model, and can serve as the Initial Conditions for the following time step. The output of the model is the forecast of future ice conditions. This is outlined in Figure 4-4. This section consists of a description of the Mid-Winter Ice Forecast model and the required System Parameters, Physical Parameters, Initial Conditions, and Boundary Conditions. This is followed by a discussion of the Model Output of the ice forecast model and a description of the application of the ice forecast model to a river system. The application discussion includes the role of supporting programs to interface the data collection program and generate the Initial Conditions and the Boundary Conditions and also to interpret the Model Output.

4-9. Hydraulic Model Description. The Hydraulic Model used is a one-dimensional, unsteady-flow model. This submodel solves two equations. The first equation is the conservation equation. It assures that the flow entering, leaving, and stored in a reach is balanced. This equation can also consider tributary inflow and other lateral inflow. It may also consider storage of flow in a

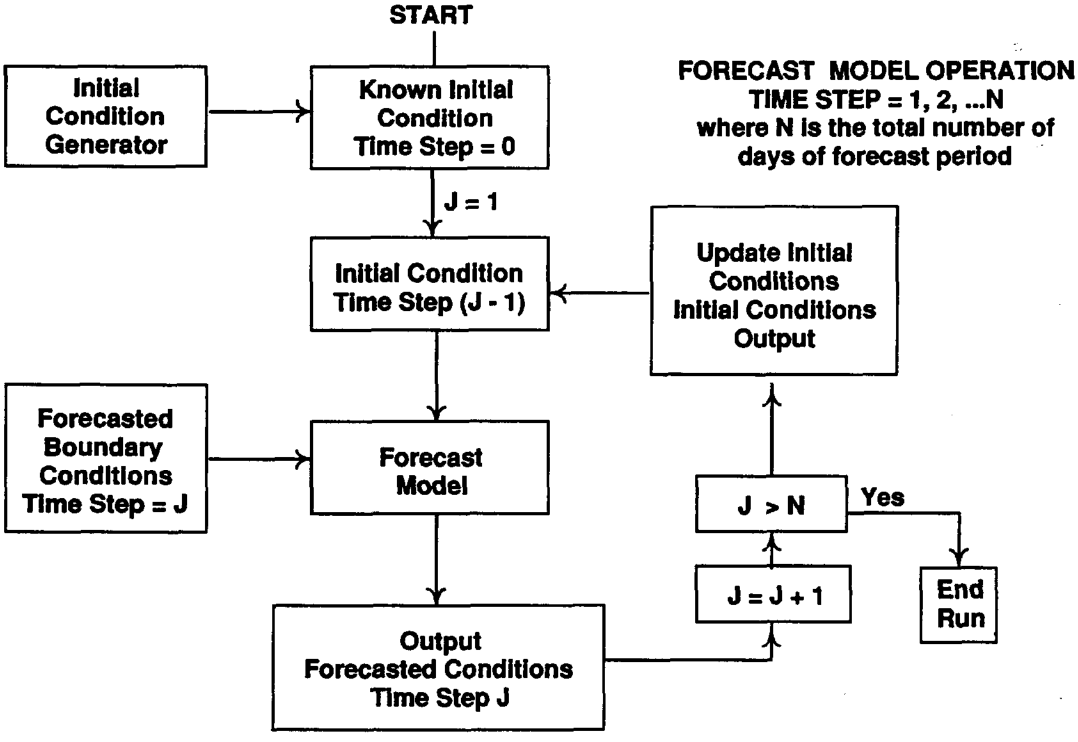

Figure 4-4. Flowchart of Mid-Winter Ice Forecast model.

flood plain. The second equation is termed the momentum equation. This equation assures that the momentum entering and leaving a reach is balanced by the forces acting on that reach. The momentum equation considers the forces of gravity, the channel friction, the hydrostatic pressure, and the possible acceleration of the flow. Both the conservation equation and the momentum equation are one-dimensional, that is, all properties are averaged over any cross section, and the only dimension considered is longitudinal or along the channel.

a. Model Equation Solutions. Taken together, the conservation and momentum equations are nonlinear, partial differential equations. Therefore, they cannot be solved directly, and they cannot be represented directly in a computer. Generally, they are represented in their finite-difference form and solved at discrete points, termed nodes. The system of nodes is used to represent the river system under consideration. Generally, a node is a point at which information about the channel geometry is known, or for which information is required, such as a lock and dam project. Each node is separated from the next by a distance (the reach length) that can have different values from one node-pair to another. The closer the spacing of nodes (i.e., the shorter the reach length), the more accurately a river can be represented and the more data that are then required. A river system (a main stem with tributaries) can be represented by such a system of nodes. It is then necessary to indicate the starting and ending node of each tributary, and the node where the tributary and main stem join. An example of such a system is shown in Figure 4-5.

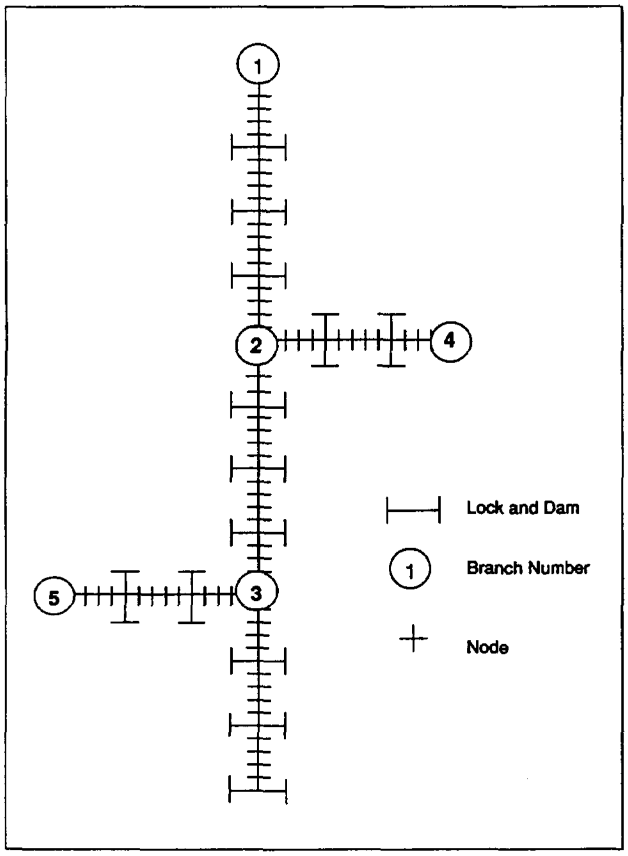

Figure 4-5. A river system represented by nodes and branches, for use in the Hydraulic Model. Note that nodes exist not only at lock and dam projects and at tributary junctions, but also wherever hydraulic and channel information is known or desired.

b. Influence of Locks and Dams. The Hydraulic Model must also be able to include the effects of locks and dams on the conservation and momentum equations. Generally, for a dam with control gates, this will mean fixing an upper pool or upper gage elevation at a lock and dam if the discharge is below a certain known value. If the discharge exceeds this value then a rating curve is supplied to determine the upper pool stage. A lock and dam with a fixed crest spillway, for example, has a rating curve to describe its upper pool elevation.

c. Ice Effects. The influence of ice must also be taken into account by the Hydraulic Model. The influence of ice will act to reduce the hydraulic radius of a cross section by increasing the wetted perimeter, reduce the cross-sectional area available for flow, and introduce a roughness that will cause an additional friction force that acts on the flow.

d. Hydraulic Model Output. The principal outputs of the Hydraulic Model are the discharge and the cross-sectional area (from which the depth, velocity, and water-surface top-width are derived) for each node for every time step.

4-10. Thermal Model Description. The Thermal Model computes a heat balance over each river reach. This submodel accounts for heat gained or lost in the reach, and assures that this is reflected in the water temperature response of that reach. However, because of the physical properties of water, it is not possible for the water temperature to decline in any appreciable way below 32°F. At this point, further heat loss from the water will result in the production of ice, and heat gain will result in the melting of ice. Once all ice in a reach has melted, further heat gain will result in a rise in the water temperature.

a. Heat Balance. Generally, the heat transfer to or from river water is dominated by the heat exchange from the open-water surface to the atmosphere. Heat exchange with the channel bed and banks is minor, as is heat gain from friction. Artificial heat sources, such as cooling water discharged from power plants, can be significant and must be included. The presence of an ice cover can greatly reduce the heat exchange with the atmosphere. In this case, the heat transferred through the ice by conduction must be calculated. The presence of an ice cover will allow heat to leave the river water, but not to be gained by the water from the atmosphere. When the ice is greater than about 2 in. thick, the heat transfer rate from the water is primarily controlled by the rate at which heat can be conducted through ice.

b. Heat Transfer from Open Water. The heat transfer from an open water surface to the atmosphere comprises several different modes. These modes include long-wave radiation, short-wave radiation, evaporation, and conduction. It has been found that the daily average heat transfer rate per unit area of open water is represented very well by a formula of the type

$$\phi = h\left(T_w - T_a\right)$$

where

ϕ = heat transfer rate per unit area

T_w = temperature of the water

T_a = temperature of the air

h = heat transfer coefficient.

The value of the heat transfer coefficient is influenced by the atmospheric stability and wind velocity, but in general can be considered to be a constant for a given region. This equation is of the same form as Equation 4-1. The difference is that here we are considering a specific area or reach of the river, while Equation 4-1 addresses the basin as a whole.

c. Heat Transfer Through an Ice Cover. Heat transfer through an ice cover is a balance of the heat lost to the atmosphere, the heat conducted through the ice, and the heat transferred from the water to the bottom of the ice cover. If more heat is transferred to the atmosphere than is transferred from the water to the ice, the ice cover will grow in thickness. If less heat is transferred, the ice cover will melt. The rate of thickening or melting is determined by the product of the latent heat of fusion of water and the heat transfer rate.

d. Temperature Response. The temperature response of a reach of river water is determined by the overall heat loss or gain from the reach, the volume of water contained in that reach, and the heat capacity of the water. The overall heat loss or gain is the product of the heat transfer rate per unit area and the surface area Both the surface area and volume of a reach are determined by the Hydraulic Model.

e. Initial Ice Formation. The initial formation of ice in a reach can be quite complex and the type of ice formed is dependent on the hydraulic conditions in that reach. Generally, the initial ice is in the form of very small disks that are well distributed through the depth of flow; this ice is termed frazil ice. Frazil will tend to collect at the water surface and to move with the general flow velocity. The Thermal Model can calculate the heat loss and calculate the amount of ice formed. However, the formation of a stationary cover ice is determined by the Ice Model (see Para. 4-11). The presence of open water implies the formation of frazil, and the presence of a stationary ice cover will imply the thickening or melting of that cover.

f. Thermal Model Output. The output of the Thermal Model is the water temperature at each node for every time step. If the water temperature is at 32°F, the volume of ice formed or melted will also be calculated. If the reach is open water, the volume of frazil formed will be determined. If the reach is ice covered, the change in thickness will be determined.

4-11. Ice Model Description. Given the hydraulic conditions of stage and velocity (determined by the Hydraulic Model), and the water temperature and volumes of ice formed or melted (determined by the Thermal Model), the Ice Model will then determine where the stationary ice covers are initiated, the manner in which they are formed, their length, their initial thicknesses, and the volume of frazil that is eroded or deposited under them. It is important to note that while the other submodels (the Hydraulic Model and the Thermal Model) are based on general physical principles (that is, the conservation of matter, momentum, and energy), the Ice Model largely reflects principles gleaned through actual observation of the behavior of river ice and the development of empirical relationships.

a. Ice Bridging. It is assumed that the initial ice formed on the river is frazil. The frazil particles will rise buoyantly and collect at the water surface to form a slush, which will then flocculate to form pans of ice. It is not possible at this time to calculate what the initial thickness of these pans will be, but a thickness for the initial pans must be entered as a Physical Parameter into the program. Therefore, the initial formation of ice will be in the form of pans whose thickness is a preset parameter. These pans will move with the flow velocity until they reach an obstacle in the flow, or until the concentration of floating ice increases to the point where the ice "bridges" naturally across the stream channel and forms a stationary cover. It is not possible at this time to calculate where these natural bridging points will occur, or under what conditions of flow and ice concentration they will occur. Therefore, the initial bridging locations must be determined through judgment and entered into the program as Physical Parameters. For example, it can be assumed that ice will initially bridge at the locations of locks and dams. Most often, ice bridges at the same locations each winter season. These locations may be at sharp bends, low velocity reaches, etc.

b. Progression by Juxtaposition. The initial formation of a stationary ice cover in a reach where an obstacle exists at the downstream end will follow the logic shown in Figure 4-6. This obstacle may be an input ice-bridging location, or the edge of the ice cover that has progressed upstream in the previous time step. The first condition to be addressed is this: Will the ice pans that arrive at the stationary cover remain floating or underturn? If they remain floating, the cover is said to progress by juxtaposition. It is assumed that if the Froude Number of the flow, defined as

$$F_D = \frac{V}{\sqrt{gD}}$$

where

V = mean velocity
g = acceleration of gravity
D = channel depth

is less than the Juxtaposition Froude Number, then the pans will not underturn and the cover will progress upstream by juxtaposition. The Juxtaposition Froude Number must be entered as a Physical Parameter. It is one of the empirical parameters used in the Ice Model.* The rate of ice

*Suggested values of the Juxtaposition Froude Number are available, or estimates can be made using semi-empirical formulas described by Ashton (1986), where the parameter is termed the "block stability criterion for underturning."

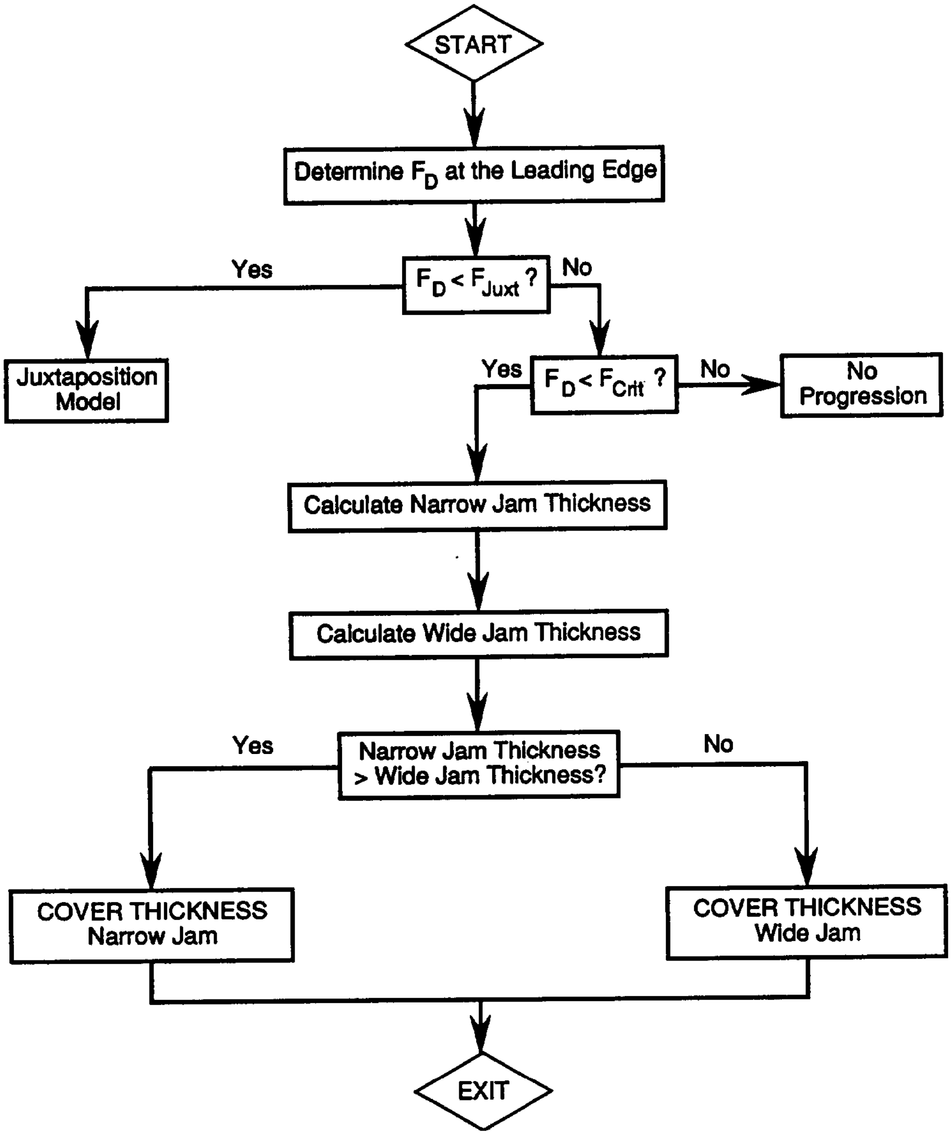

Figure 4-6. Flowchart of the logic used in the Ice Model for determining whether the upstream ice cover progression is by juxtaposition or by jamming (with the associated narrow-jam or wide-jam thicknesses), or whether there is no progression of the ice cover.

cover progression upstream will be determined by the concentration of arriving ice, the velocity of the arriving ice, the thickness of the cover, the porosity of the cover, and the fraction of the total ice flow going into the cover formation. (The porosity of the cover and the fraction of the total ice flow going into the cover are also entered as Physical Parameters.) If, on the other hand, the Froude Number of the flow is greater than the Juxtaposition Froude Number, then the pans will underturn, and may nor may not progress upstream. If the pans do progress upstream under this condition, they do so by jamming rather than by juxtaposition.

c. Limit of Ice Cover Progression. If the Froude Number of the flow exceeds the Juxtaposition Froude Number, it is necessary to check and see if the Froude Number of the flow is greater than a limiting value of the Froude Number for progression. If this is true, no ice cover progression is possible. All the arriving ice will be swept under the existing ice cover and carried downstream. This means that, until the hydraulic conditions change, the river will remain as ice-free open water upstream of this point. This limiting value of the Froude Number for progression is also an empirical value, entered as a Physical Parameter; suggested values are available.

d. Wide and Narrow Ice Jams. If the Froude Number of the flow exceeds the Juxtaposition Froude Number, but is less than the limiting value of the Froude Number for ice cover progression, then the ice cover can progress in one of two modes. These modes are termed the narrow-jam and wide-jam modes. These modes reflect the balance of forces acting on the ice cover.

(1) In the wide-jam mode, the ice cover must thicken to transfer the forces acting on the cover to the channel banks. The forces acting on the cover are the bottom friction ascribable to the flow and the component of the weight of the cover parallel to the water surface caused by the slope of the water surface. These forces are resisted by the friction of the ice against the channel banks and by any cohesion with the channel banks. It is assumed that the forces acting on the cover are in equilibrium with the resisting force of the channel banks at every point along the channel. The thickness of ice required to provide this equilibrium is termed the equilibrium ice jam thickness, and is calculated assuming that the ice acts as a passive granular material. The Physical Parameters that are required are the underside roughness of the ice cover, the coefficient of friction of the ice with the banks, the coefficient of passive stress for granular ice, the bank cohesion, and the porosity of the ice cover. Once the equilibrium ice jam thickness has been calculated, the progression rate is determined with the same procedure as before.

(2) In the narrow-jam mode, it is assumed that the thickness of the ice cover is determined by the hydraulic conditions at the leading edge of the ice cover. Forces acting on the cover are not a consideration. Specifically, it is necessary that the ice cover be thick enough so that a “no-spill” condition is satisfied. That is, the cover is thick enough to resist the sinkage caused by the acceleration of flow beneath the leading edge of the cover.

(3) Generally, it is not possible to determine beforehand whether an ice cover will progress in the wide-jam or narrow-jam modes. The thickness that will result from each mode is calculated and the mode that results in a greater thickness is used.

e. Conservation of Moving Ice. The Ice Model balances the concentration of moving ice for each time step. Ice that reaches a stationary ice cover, and does not go into the formation of the ice cover via one of the modes described above, is assumed to be transported under the ice cover. This ice can be deposited under the ice cover, and is considered to be deposited frazil. The deposited ice can then be eroded if the velocity of the water increases sufficiently. The rate of deposition to the underside of the ice cover is determined by a mass balance calculation on the transported ice. The Physical Parameters required are the probability of deposition of an ice particle that reaches the ice/water interface, the buoyant velocity of the frazil particle, and the critical velocity for deposition. If the flow velocity is above the critical velocity for deposition, the frazil will not be deposited. Erosion of the deposited frazil takes place when the local flow velocity under a frazil deposit increases beyond the critical velocity for erosion. The Physical Parameter that is required here is the critical velocity for erosion.

f. Ice Cover Stability. After an ice cover has been formed, it can be lost when the forces acting on the cover exceed the ability of the cover to transfer these forces to the channel bank. This will happen if the hydraulic conditions change, or if the ice cover thickness is reduced by melting. Therefore, at each time step a force balance must be determined on the ice cover in each reach. The friction on the ice cover from the flow, and the component of the weight of the cover parallel to the water surface caused by the slope of the water surface, are balanced against the ice cover's ability to resist the applied forces. The ice cover strength is determined by the ice thickness, the coefficient of friction of the ice with the banks, and the bank cohesion. If the force acting on the ice cover exceeds the ability of the ice cover to resist that force, the ice cover is then considered to collapse and become floating and mobile ice.

4-12. System Parameters. System Parameters are data that describe the physical river system that is to be modeled, and the manner in which the model is to operate. Generally, these System Parameters do not change their values as the model is run. The following are required System Parameters:

—Number of tributary branches.
—Number and location of nodes.
—Number and location of locks and dams.
—Number of lateral inflows.
—Time step length.
—Total time of model run.

4-13. Physical Parameters. Physical Parameters are data that describe the physical processes that are being modeled. Generally, these are physical constants and do not change their value while the program is being run. These constants are either measured in the field, determined during model calibration, estimated from observation and laboratory experiment, or known from physical principles.

a. Hydraulic Model Physical Parameters.

(1) Measured in the Field.
—Channel geometry of each node.
—Flood plain areas.

(2) Determined from Model Calibration.
—Channel roughness.
—Contraction and expansion coefficients.

(3) Physical Principle.
—Density of water.

b. Thermal Model Physical Parameters.

(1) Determined from Model Calibration.
—Air-water heat transfer coefficient.
—Ice-water heat transfer coefficient.

(2) Physical Principles.
—Density of water.
—Heat capacity of water.
—Thermal conductivity of ice.
—Heat capacity of ice.
—Latent heat of fusion of ice.
—Density of ice.

c. Ice Model Physical Parameters.

(1) Estimated from Observation and Laboratory Experiment.
—Buoyant velocity of frazil particles.
—Probability of ice particle depositing on cover.
—Critical velocity of frazil deposition.
—Critical velocity of frazil erosion.
—Coefficient of passive stress.
—Ratio of longitudinal stress to bank friction.
—Ice-bank cohesion.
—Bridging flag at each node.
—Underside roughness coefficient of ice cover.
—Juxtaposition Froude Number.
—Limiting value of the Froude Number for progression.
—Ice cover porosity.
—Deposited frazil porosity.
—Initial ice pan thickness.
—Fraction of total ice flow going into the ice cover formation.

(2) Physical Principles and Parameters Determined from Model Calibration. As noted in Paragraph 4-11, the Ice Model does not have Physical Parameters based on physical principles nor determined by means of model calibration.

4-14. Initial Conditions. The Initial Conditions are those that describe the physical conditions of the river system at the time that the forecast is made. The following Initial Conditions must be known at each node.

a. Hydraulic Model Initial Conditions.
—Water surface elevation.
—Discharge.

b. Thermal Model Initial Condition.
—Water temperature.

c. Ice Model Initial Conditions.
—Floating ice concentration.
—Ice cover length.
—Ice cover thickness.
—Deposited frazil thickness.

4-15. Boundary Conditions. The Boundary Conditions cannot be determined by the Mid-Winter Ice Forecast model. They are the parameters (forecasted by other means) that drive the model. The Boundary Conditions can change with each time step.

a. Hydraulic Model Boundary Conditions.
—Tributary discharge.
—Lateral inflows.
—Downstream stage.

b. Thermal Model Boundary Conditions.
—Tributary water temperature.
—Lateral inflow water temperature.
—Air temperature at every node.

c. Ice Model Boundary Conditions. There are currently no Boundary Conditions to be entered in the Ice Model. However, if known, the ice concentration of the tributaries and lateral inflows could be entered.

4-16. Model Output. The output of the Mid-Winter Ice Forecast model, in general, consists of updated values of the Initial Conditions based on the input Boundary Conditions. Each of the three submodels produces its own output. The output can be specified at each node and at each time step.

a. Hydraulic Model Output. The output of the Hydraulic Model consists of the stage and discharge at each node at each time step. The mean velocity can also be calculated since the cross section geometry is known.

b. Thermal Model Output. The output of the Thermal Model consists of the water temperature at each node at each time step.

c. Ice Model Output. The output of the Ice Model consists of the following for each node at each time step:

—Concentration of moving ice.
—Presence or absence of an ice cover, and if an ice cover is present, the length and thickness of that ice cover.
—Thickness of deposited frazil.

4-17. Model Calibration. The initial calibration setup of the Mid-Winter Ice Forecast model is not described in detail. However, in general, calibration of the model consists of adjusting the values of the Physical Parameters in each of the submodels so that the Model Output accurately reproduces the observed conditions. This procedure is necessary because in many cases there is no means of actually measuring the required Physical Parameters.

a. Hydraulic Model Calibration. Calibration of the Hydraulic Model consists of adjusting the roughness coefficients that determine the resistance of the channel to flow. Generally, the roughness coefficients are adjusted so that, at observed discharges, the corresponding observed water elevations are matched.

b. Thermal Model Calibration. Calibration of the Thermal Model consists of adjusting the heat transfer coefficients that determine the heat transfer rates from the water to the air, and from the water to the underside of the ice cover.

c. Ice Model Calibration. A telling indication of the uncertain knowledge of river ice is the large number of parameters that could be adjusted during the calibration of an Ice Model. Generally, every Physical Parameter listed under the Ice Model (Para. 4-13d can be adjusted, as a definite value for each parameter cannot yet be calculated from our understanding of ice. physics. Unfortunately, this is not a very satisfactory state of affairs. It is recommended that suggested values of the Physical Parameters be used and not adjusted, unless direct evidence of the need for adjustment is produced.

4-18. Model Operation. A general overview of the operational setup of the Ice Forecasting System is shown in Figure 4-7. The system may be divided into four general components: Data Collection and Transmission, Data Reduction and Data Base Management, Initial Conditions and Boundary Conditions Generators, and the Mid-Winter Ice Forecast model itself.

a. Field Data Collection and Transmission. Data collected and transmitted for the model at present are water temperature, air temperature, and water-surface stage. This information is collected by Data Collection Platforms (DCP's) and transmitted via Geostationary Observational Environmental Satellite (GOES) to a down-link at a central location. The equipment and setup of a DCP with the appropriate sensors are addressed in Chapter 5. Thermistors, which change resistance in response to temperature change, are used to measure temperature. As DCP’s can generally only measure voltages, a voltage divider circuit must be used to convert the thermistor resistance to a voltage that can be measured by the DCP. Generally, the following data must be

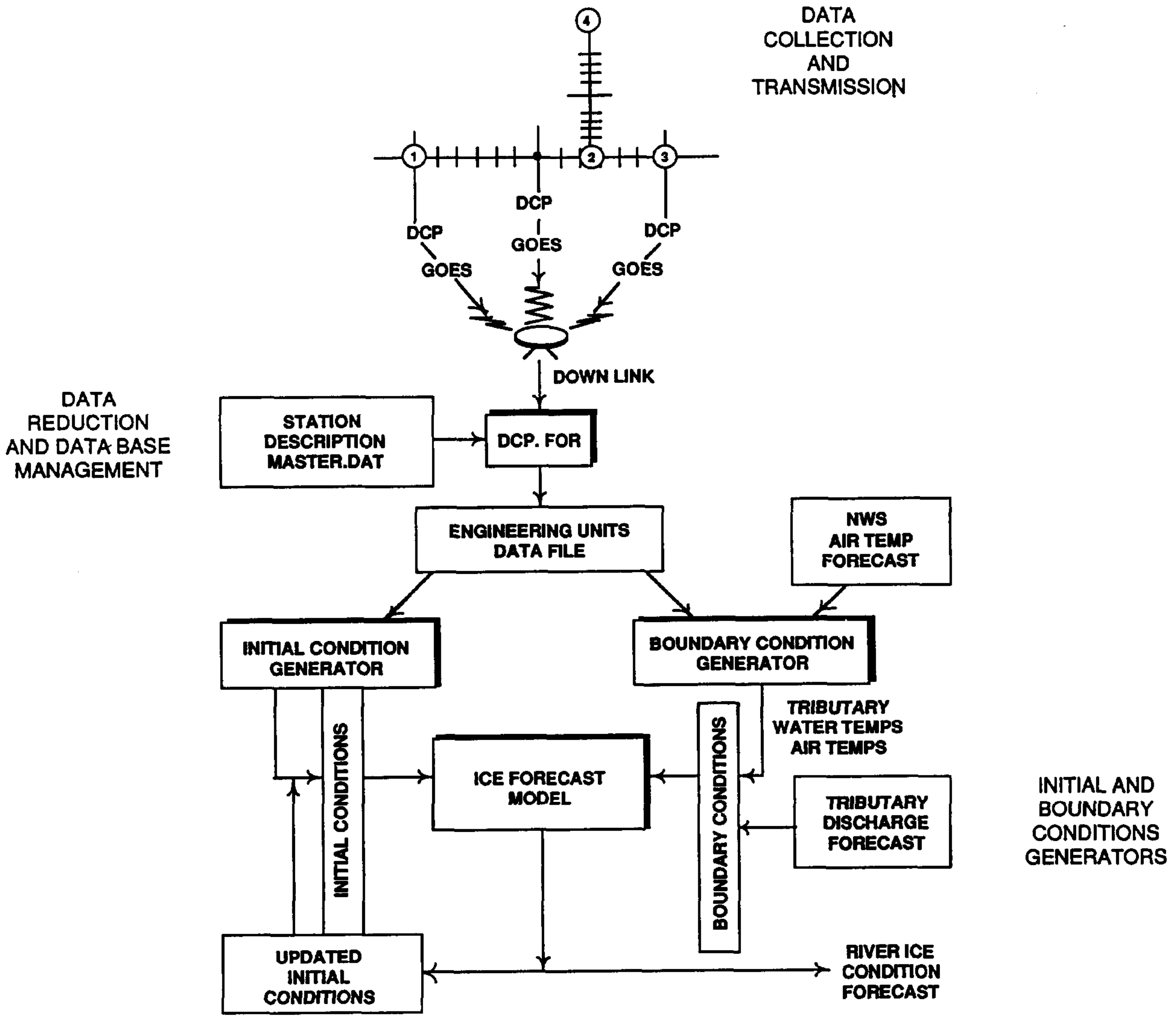

Figure 4-7. Overall flowchart of the Ice Forecasting System, within which the Mid-Winter Ice Forecast model operates under the support of Data Collection and Transmission, Data Reduction and Data Base Management, and Initial Conditions and Boundary Conditions Generators (DCP.FOR and MASTER.DAT are computer program names).

transmitted to accurately determine temperature-the measured voltage across the voltage divider circuit, the measured voltage across the thermistor, and a measurement of the voltage across a reference resistor. The last measurement is necessary to correct for any impedance mismatch.

b. Data Reduction and Data Base Management. The transmissions from the DCP's are coded, and these coded transmissions must be decoded and converted to the proper engineering units. To determine temperature accurately from thermistor measurements, the actual thermistor resistance must be determined (based on the transmitted voltages), the resistance must be corrected for any impedance mismatch, and then the thermistor matched up with the proper calibration constants to convert the thermistor resistance to a temperature. A program (DCP.FOR) was developed for this purpose. DCP.FOR has a highly flexible structure for describing a particular DCP site, and this description can easily be modified or updated. This is particularly important during the setup of large data collection networks, when sensors may often be moved, recalibrated, or replaced. DCP.FOR can also decode the messages from any other meteorological sensor that has a linear output. DCP.FOR creates an output file whose format is fixed, but allows any arrangement of sensors as input to the DCP. A single file is created for each station for each month. The measured value of each sensor, in engineering units, is stored in a fixed format in the file. This allows a flexibility in the sensor configuration at the DCP, while maintaining a data base whose format is fixed. Currently, the output file of DCP.FOR is being interfaced with the Corps DSS data base system.

c. Initial Conditions and Boundary Conditions Generators. These are programs that take the actual field data and the forecasted values of air temperature and tributary discharge to create the proper Initial Conditions file and Boundary Conditions file for the Mid-Winter Ice Forecast model. These are discussed in more detail in Paragraphs 4-20 and 4-21.

d. Mid-Winter Ice Forecast Model. The Mid-Winter Ice Forecast model was discussed previously. The model (using the Initial Conditions and the Boundary Conditions created by the Initial Conditions and Boundary Conditions Generators) prepares the forecast of predicted ice conditions. Two different modes of operation will be described: the Update Mode and the Forecast Mode (see Para. 4-22).

4-19. Location of Field Measurement Sites. Ideally, a field measurement site could be located at each node of the model. The site would provide information on the water stage, discharge, air temperature, and water temperature. However, this would be prohibitively expensive, and the amount of data generated would quickly bury any practical data management scheme. In fact, field measurement sites should be kept to a minimum and located where they will provide the optimum information to allow the most accurate creation of the Initial Conditions and Boundary Conditions as input to the Mid-Winter Ice Forecast model. In general, the following guidelines apply:

—Field sites to measure water temperature should be located at the upstream end of the main stem and at the upstream end of each tributary to be modeled.

—Field sites to measure air and water temperature should be located throughout the river system to be modeled, and in sufficient density to provide a representative "picture" of the actual conditions. To determine this, some background study will be required to understand the meteorological and climatological conditions of the river system to be modeled. For example, on the Ohio River, field sites were located at an average spacing of about 80 miles along the river. However, in the upstream reaches of the Ohio River, where the winter climate varied over rather short distances, the stations were much closer. A good indication of climatic variation can be seen on a map indicating average freezing degree-days for a given winter month; January is the best month to represent this variation.

—A field site should be located at the downstream end of the river system that is modeled.

4-20. Initial Conditions Generator. The Initial Conditions required in the model are listed in Paragraph 4-14.

a. Hydraulic Model. The generation of Initial Conditions for the Hydraulic Model is not discussed in detail here. It can be assumed that the Initial Conditions of stage and discharge are available from a previous model run (Update Mode), from a steady-state backwater measurement, or from physical measurement with interpolation.

b. Thermal Model. The Initial Condition of water temperature for the Thermal Model at each node can be determined from a previous model run (Update Mode) or from the reported measurements from the field sites. To determine the water temperature at each node from the field sites, the procedure is to first determine the average water temperature at each site for the previous 24 hours. Then, for the main stem, linearly interpolate the water temperature at each node between the field sites. For the tributaries, linearly interpolate the water temperature between the site at the upstream end of the modeled tributary section and the temperature calculated in the previous step for the main stem at the confluence of the tributary and the main stem. If no upstream site is available, it has been found that a reasonable approximation is to use the temperature of the main stem at the confluence as the temperature for the entire reach of the modeled tributary.

c. Ice Model. The Initial Conditions for the Ice Model are the floating ice concentration, ice cover length and thickness, and thickness of deposited frazil. It is not possible to physically measure the concentration of floating ice, although it can be visually estimated by experienced personnel during overflights. The ice cover length can also be estimated from visual observation, preferably by aerial videotaping of the entire reach to be modeled, as described in Chapter 5. Generally, the solid ice cover and frazil thicknesses are not available, except at a very few locations. With the Ice Model data so scarce and incomplete, the realistic alternative is to generate the initial ice conditions from previous model runs (Update Mode).

4-21. Boundary Conditions Generator. The Boundary Conditions required are listed in Paragraph 4-15. The Boundary Conditions are independently forecasted parameters that drive the model. Generally, the Boundary Conditions can change with every time step. Inaccurate forecasts of future Boundary Conditions will produce inaccurate model results.

a. Hydraulic Model. The generation of Boundary Conditions for the Hydraulic Model is not discussed in detail here. The forecasts of tributary and lateral discharges and downstream stage can be determined by a variety of means.

b. Thermal Model. The principal Boundary Condition of the Mid-Winter Ice Forecast model is the air temperature Boundary Condition of the Thermal Model. Generally, the daily average air temperature is used as the Boundary Condition. Forecasts of maximum and minimum air temperature are available from the NWS. A good estimate of the daily average is the mean of the maximum and minimum. Forecasts of the air temperature will undoubtedly be available at several locations throughout the river system where the Mid-Winter Ice Forecast model is to be used. A linear interpolation between the air temperature forecast locations is used to determine the air temperature Boundary Condition at each node.

(1) The forecasts of the tributary water temperature are made using the total watershed approach that is employed in making the Long-Term Water Temperature Forecasts, described in Section I. Information that is required includes the response coefficient and the equivalent water temperature, the actual water temperature on the day the forecast is made, and the forecasted air temperatures. With this information, based on the total watershed approach, a forecast of the tributary water temperature Boundary Condition can be made.

(2) The forecasts of the lateral inflow water temperature can be used to include the influence of artificially heated discharge from power plants, etc. Generally, the lateral inflow water temperatures will not be a factor, as these will be very near or at the main stem water temperature. For locations where heated discharges may be important, the lateral inflow water temperature can be put at a set value above the nearest forecasted tributary water temperature, representing the heat added by a power plant or industrial facility.

c. Ice Model. There are generally no forecasts of ice conditions suitable for use as forecasted Boundary Conditions of the Ice Model. If an ice run is expected on a tributary, this could be used as a Boundary Condition as long as the ice concentration can be estimated.

4-22. Modes of Operation. The Mid-Winter Ice Forecast model can be operated in two modes, a Forecast Mode and an Update Mode. The Forecast Mode starts with the existing Initial Conditions, and uses forecasted values of the Boundary Conditions to produce the Model Output. The Update Mode starts with the Initial Conditions that existed the last time the model was run. If the model is operated daily, for example, the Initial Conditions are those existing on the previous day. The actual values of the Boundary Conditions, measured at the field sites, are then used to produce the Model Output. In this way the previous existing conditions are updated to reflect the present existing conditions. Generally, the model is run twice on any day a forecast is made, once to update the Initial Conditions and once to forecast the future ice conditions.

4-23. Model Results. A sample of the Model Output over an entire winter season is shown graphically in Figure 4-8. In this simulation, actual recorded air temperatures and tributary discharges were used. The ice bridging locations were chosen to be at each lock and dam, consistent with observation. The simulation is for the Upper Ohio River, and the location of each lock and dam is indicated. The period covered by the simulation in Figure 4-8 is from 22 December 1985 through 12 February 1986, and the presence of ice is shown as determined by the model. In Figure 4-9, a sample 5-day forecast is shown, also for the Upper Ohio River. This forecast was prepared based on forecasted air temperatures and the actual Initial Conditions on the day that the forecast made.

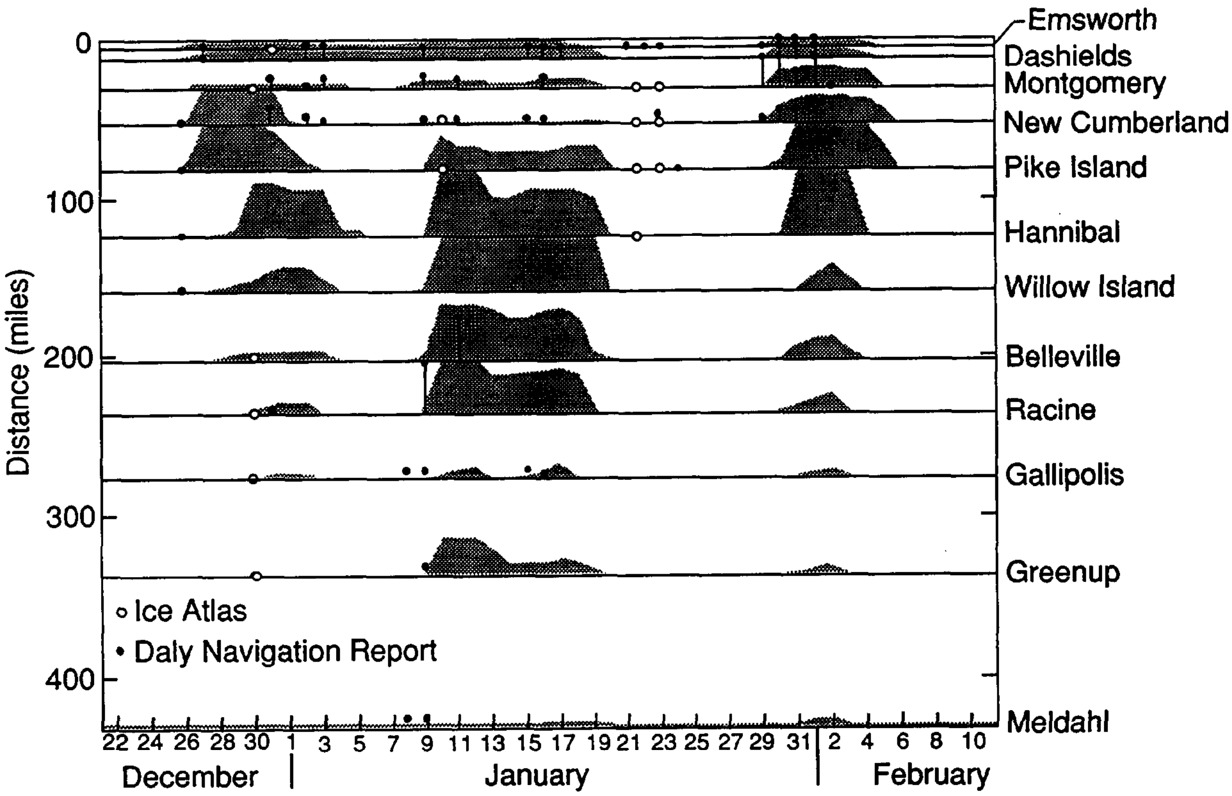

Figure 4-8. Portrayal of the output of the Ice Forecasting System for the upper Ohio River during the 1985-86 winter. The shaded areas indicate forecasted ice cover on the river; elsewhere the river was forecasted to be open. Choosing a river location on the diagram and moving across the diagram horizontally gives a time-based summary of the sequence of forecasted ice cover throughout the winter for that location. Similarly, choosing a date during the winter and moving vertically up or down the diagram gives a location-based summary of forecasted ice cover for the Upper Ohio on that particular date. Shown for comparison is ice coverage information based on daily navigation reports issued by the Pittsburgh and Huntington Districts, and an ice atlas (Gatto et al. 1987b) based on aerial videotapes.

ICE COVER CONDITIONS ON 12-20-89

DAM	LENGTH MILES	ICE THICKNESS FEET	PER CENT OF POOL WITH ICE	WATER TEMP DEG F	AIR TEMP DEG F
EMSWORTH	0.00	0.00	0	32.70	14.00
DASHIELD	2.96	0.18	44	32.00	14.00
M-GOMERY	0.00	0.00	0	33.37	14.00
NEW CUM	15.20	0.24	79	32.00	14.07
PIKE IS	29.70	0.16	100	32.00	14.18
HANNIBAL	0.30	0.00	5	32.00	14.32
WILL IS	0.47	0.00	10	32.00	14.43
BELVILLE	0.00	0.00	0	32.23	14.56
RACINE	0.00	0.00	0	32.18	14.67
GLPOLLIS	0.00	0.00	0	32.70	14.74
GREENUP	0.00	0.00	0	33.26	14.85
MELDAHL	0.00	0.00	0	35.20	15.01

ICE COVER CONDITIONS ON 12-21-89

DAM	LENGTH MILES	ICE THICKNESS FEET	PER CENT OF POOL WITH ICE	WATER TEMP DEG F	AIR TEMP DEG F
EMSWORTH	0.00	0.00	0	32.88	8.01
DASHIELD	2.96	0.36	44	32.05	8.01
M-GOMERY	0.00	0.00	0	33.37	8.01
NEW CUM	15.20	0.34	79	32.07	8.40
PIKE IS	29.70	0.43	100	32.00	8.91
HANNIBAL	42.30	0.17	100	32.00	9.64
WILL IS	35.30	0.22	100	32.00	10.18
BELVILLE	41.20	0.12	100	32.00	10.83
RACINE	33.60	0.09	100	32.00	11.35
GLPOLLIS	1.89	0.00	22	32.00	11.70
GREENUP	3.64	0.00	74	32.00	12.20
MELDAHL	0.00	0.00	0	34.07	12.99

ICE COVER CONDITIONS ON 12-22-89

DAM	LENGTH MILES	ICE THICKNESS FEET	PER CENT OF POOL WITH ICE	WATER TEMP DEG F	AIR TEMP DEG F
EMSWORTH	1.73	0.00	43	32.00	1.00
DASHIELD	3.56	0.44	53	32.00	1.00
M-GOMERY	0.00	0.00	0	32.05	1.00
NEW CUM	15.20	0.42	79	32.31	1.40
PIKE IS	29.70	0.61	100	32.00	1.90
HANNIBAL	42.30	0.50	100	32.00	2.64
WILL IS	35.30	0.51	100	32.00	3.18
BELVILLE	41.20	0.44	100	32.00	3.83
RACINE	33.60	0.39	100	32.00	4.35
GLPOLLIS	40.70	0.30	100	32.00	4.69
GREEN-UP	60.80	0.31	100	32.00	5.22
MELDAHL	0.00	0.00	0	32.76	6.01

Figure 4-9. Typical output information from the Mid-Winter Ice Forecast model, covering a five-day period on the upper Ohio River.

ICE COVER CONDITIONS ON 12-23-89

DAM	LENGTH MILES	ICE THICKNESS FEET	PER CENT OF POOL WITH ICE	WATER TEMP DEG F	AIR TEMP DEG F
EMSWORTH	6.00	0.48	100	32.00	-0.99
DASHIELD	7.10	0.55	100	32.00	-0.99
M-GOMERY	18.40	0.41	100	32.00	-0.99
NEW CUM	22.70	0.46	100	32.00	-0.44
PIKE IS	29.70	0.72	100	32.00	0.28
HANNIBAL	42.30	0.80	100	32.00	1.31
WILL IS	35.30	0.77	100	32.00	2.07
BELVILLE	41.20	0.74	100	32.00	2.97
RACINE	33.60	0.70	100	32.00	3.69
GLPOLLIS	40.70	0.64	100	32.00	4.17
GREENUP	60.80	0.64	100	32.00	4.89
MELDAHL	94.20	0.12	100	32.00	6.01

ICE COVER CONDITIONS ON 12-24-89

DAM	LENGTH MILES	ICE THICKNESS FEET	PER CENT OF POOL WITH ICE	WATER TEMP DEG F	AIR TEMP DEG F
EMSWORTH	6.00	0.81	100	32.00	0.00
DASHIELD	7.10	0.87	100	32.00	0.00
M-GOMERY	18.40	0.76	100	32.00	0.00
NEW CUM	22.70	0.80	100	32.00	0.46
PIKE IS	29.70	0.83	100	32.04	1.09
HANNIBAL	42.30	0.98	100	32.00	1.98
WILL IS	35.30	0.98	100	32.00	2.62
BELVILLE	41.20	0.98	100	32.00	3.42
RACINE	33.60	0.94	100	32.00	4.03
GLPOLLIS	40.70	0.89	100	32.00	4.44
GREENUP	60.80	0.88	100	32.00	5.05
MELDAHL	94.20	0.50	100	32.00	6.01

Figure 4-9 (Continued).